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Dimensional Measurements of Three Tubes by Computed Tomography¹

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Low density polyethylene (LDPE), copper (Cu), and gold (Au) tubes were scanned on KCAT to identify and evaluate the impact of phase effects on quantitative object recovery. These tubes are phantoms for high energy density capsules.[Logan, et al. 2004] Digital radiographs for each tube are shown in Figure 1. The LDPE tube was scanned at 60 kV, while the Cu and the Au tubes were scanned at 140 kV. All tubes were scanned at a magnification of 3, with approximately 100-mm distance between the exit plane of the tube and the scintillator. Notice the prominence of the outer bright and inner dark edges for the LDPE tube DR, and their absence from the Cu and Au tube DRs. The bright and dark edges are a result of change in phase of the x-rays. The x-ray fluence is partly attenuated and partly refracted. The location near the outer edge of the tube appears to be more attenuating since those x-rays have refracted to locations just outside the tube. Alternatively, the added counts from the refraction result in intensities that are greater than the incident intensity effectively representing a “negative attenuation”. This results in more counts in that location than in the incident intensity image violating the “positive-definite” requirement for standard CT reconstruction methodologies. One aspect of our CT processing techniques remove some of this signal on the outside of the object. The goal of this paper is to evaluate the accuracy of our dimensional measurement methods for mesoscale object inspection.

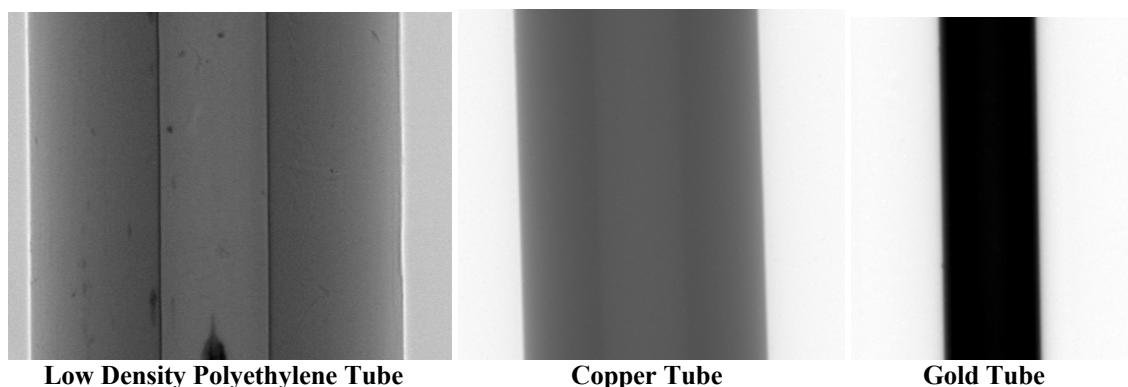


Figure 1 – Transmission digital radiographs of tube test objects.

CT cross sectional images of the three tubes are shown in Figure 2. Notice the bright edges for the LDPE tube and the deviation from a circle on the inner edges of the Cu and Au tubes. Dimensional measurements of the tubes are summarized in Table 1. For the LDPE tube the outer-diameter micrometer² and CT measurements³ are, within uncertainty, the same, however they are about 2% lower than the manufacturer provided specification⁴. The wall thickness (see Appendix) of the LDPE tube from the CT data (Figure 3) was determined to be 0.389 ± 0.009 . If the manufacturer specification for the wall thickness is correct, it appears the bright edges in the CT LDPE data result in an overestimate of the wall thickness by at least 30 μm . It is clear that if we do not account for the phase effects the dimensional measurements can be off by a considerable amount, in this case 39 μm on average, when we need μm accuracies.

¹ This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

² The micrometer measurements were performed by two people. The average of these two measurements with uncertainty are quoted in Table 1.

³ For all the tubes the outer-diameter CT measurements were determined by the average of two methods. One method was the average of seven estimates of the diameter from line outs through the center. The other method was to determine the best fit circle to the outer boundary.

⁴ All three tubes were purchased from Goodfellow <http://www.goodfellow.com/csp/active/gfwelcome.csp>. There are no uncertainties in the manufacturer outer-diameters or wall thicknesses specified.

For the Cu tube, the outer-diameter micrometer measurements resulted in 0.625 ± 0.007 mm and agree very well with the measured CT data (Figure 4) outer diameter value of 0.625 ± 0.002 mm. These measured values are 0.125 mm or 20% less than the manufacturer specified value of 0.75 mm. The measured CT wall thickness for the Cu tube is 0.197 ± 0.008 mm, which is at least 0.015 mm less than the manufacturer specified thickness of 0.22. It may be that the actual wall thickness is 12% smaller than the manufacturer specified value given the 20% smaller outer-diameter micrometer and CT measurements of the tube relative to the manufacturer specified value. It is useful to note the variation in the inner wall of the Cu tube as revealed by the CT data in Figure 2.

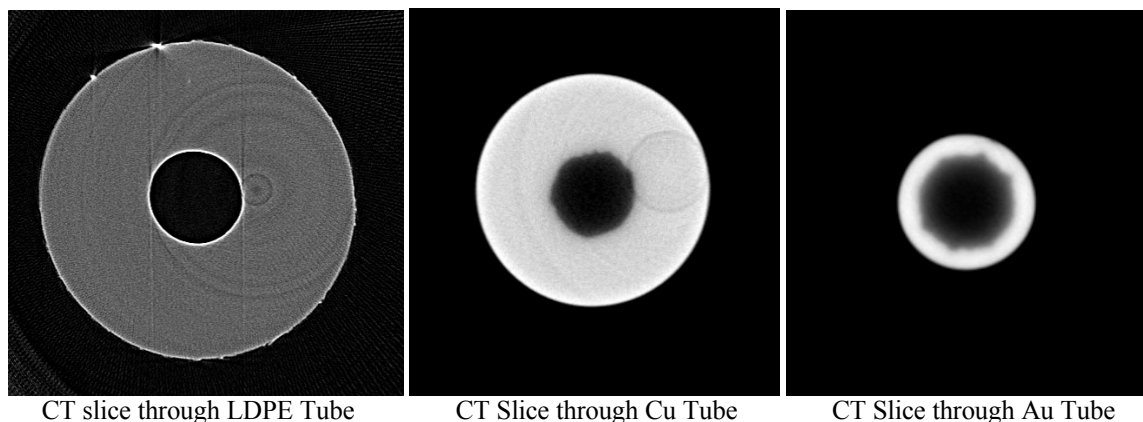


Figure 2 – CT cross sections of the three tubes. Note the bright edges for the LDPE tube and the deviation from a circle on the inner edges of the Cu and Au tubes.

For the Au tube, as with the Cu tube, the micrometer and CT measured outer-diameter measurements are in good agreement. However these values are on average 10% lower than the manufacture specified diameter of the Au tube as shown in Table 1. The mean wall thickness of the Au tube was measured by CT (see Figure 5) to be 0.042 ± 0.002 and is 19% less than the manufacturer specified value of 0.050 mm. Furthermore it is useful to note the variation in the inner wall of the Au tube as revealed by the CT data in Figure 2. Given this you wonder how the manufacturer actually determines the wall thickness.

Table 1. Comparison of tube specifications from manufacturer and resulting measured values.

Tube	Goodfellow specified outside diameter (mm)	Micrometer measured* outside diameter (mm)	CT measured outside diameter (mm)	Goodfellow specified wall thick (mm)	Mean CT measured wall thickness (mm)	Goodfellow Density (g/cm ³)
LDPE ^Δ	1.100	1.075 ± 0.007	1.08 ± 0.01	0.350	0.389 ± 0.009	0.92
Cu	0.750	0.625 ± 0.007	0.625 ± 0.002	0.220	0.197 ± 0.008	8.96
Au	0.300	$0.270 \pm 0.007^+$	0.28 ± 0.02	0.050	0.042 ± 0.002	19.32

^Δ Low Density PolyEthylene

* The micrometer measurements were performed by two people. The average of these two measurements with uncertainty are quoted.

⁺ The two Au tube micrometer measurements were the same value; we choose to use the average of the LDPE and Cu tubes uncertainty as the Au tube uncertainty value.

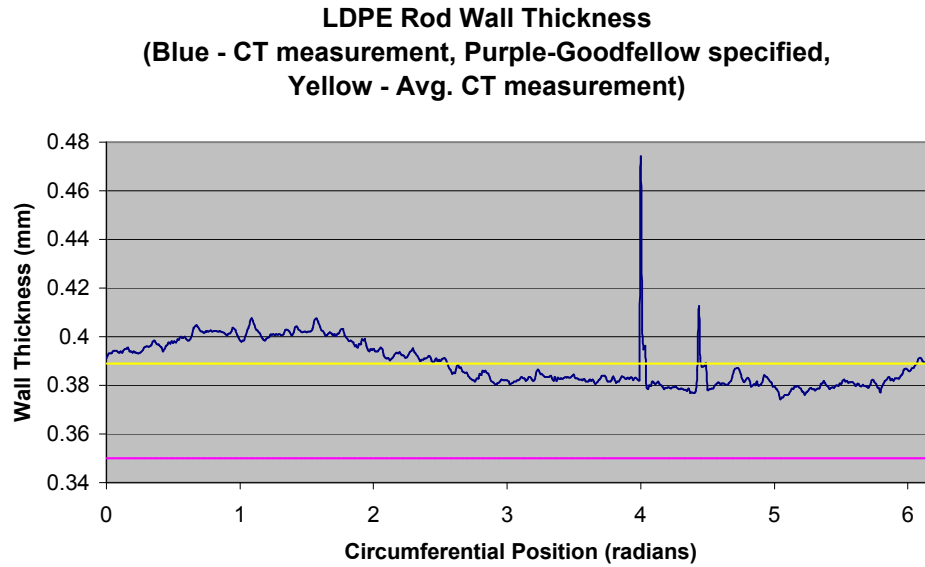


Figure 3 – Low density polyethylene tube results of the CT wall thickness measurements (blue) and average value (yellow) compared to the manufacturer specified wall thickness (purple). The two outliers (peaks) are due to the extra material on the outside edge of the LDPE tube shown as white spots in Figure 2 at 10-12 o'clock. Overall the results reveal that the inner and outer walls (circles) are not concentric.

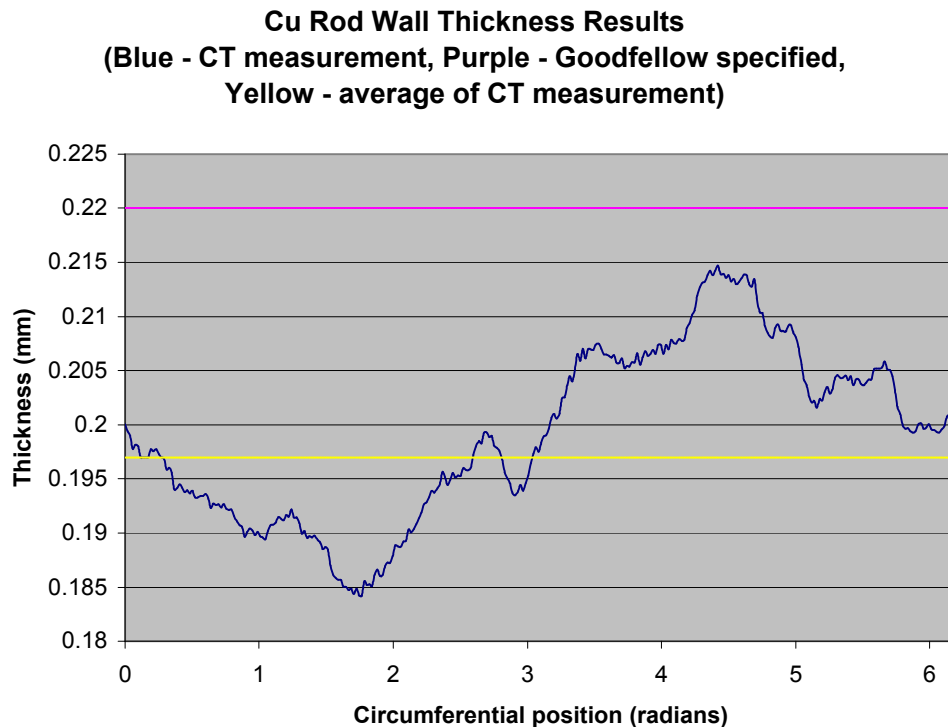


Figure 4 – Copper tube results of the CT wall thickness measurements (blue) and average value (yellow) compared to the Goodfellow specified wall thickness (purple). Overall the results reveal that the inner and outer walls (circles) are not concentric and have a perturbation on the inner wall as shown in Figure 2 for the Cu-tube CT slice.

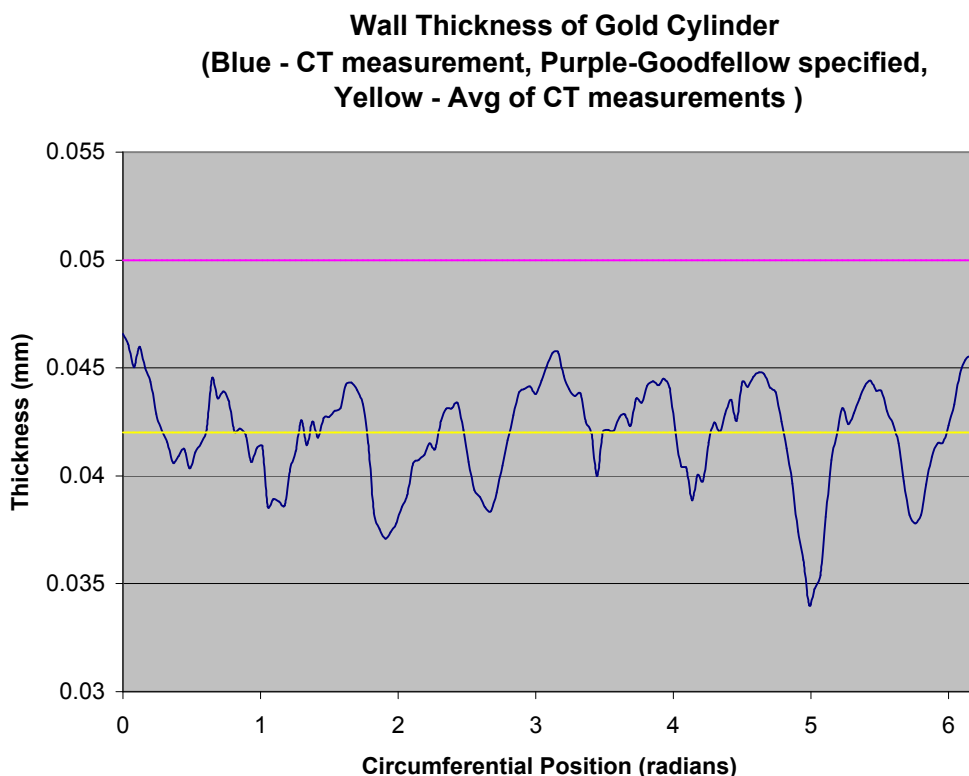


Figure 5 – Gold tube results of the CT wall thickness measurements (blue) and average value (yellow) compared to the manufacturer specification wall thickness (purple). Overall the results reveal that the inner and outer walls (circles) are concentric but have a perturbation on the inner wall as shown in Figure 2 for the Au tube CT slice.

From the LDPE tube CT results the presence of phase effects impacts our ability to quantitatively measure features in mesoscale objects. The LDPE tube includes phase effects on both the inner and outer edges. For this tube, while the CT measurements of the outer diameter are within uncertainty of the micrometer measured value but differ from the manufacturer specified value by 25 μm and the wall thickness is over estimated by a considerable amount, at least 30 μm (8% of the manufacturer specified wall thickness). It is clear if we do not account for the phase effects the dimensional measurements can be off by a considerable amount, in this case 30 μm , when we need μm accuracies.

For the copper and gold tubes the outer-diameter micrometer and CT measurements track, but there is discrepancy with the manufacturer specifications. On average the measured Cu and Au tubes outer diameter and wall thicknesses are ~20 and ~10% smaller than the manufacturer's values, respectively. The uncertainty in the wall-thickness measurements for the copper and gold tubes reflects the variation on the inner edge of these tubes. In both of these cases there are very few phase effects in the DR or CT data.

The discrepancies between the micrometer and CT measurements and the manufacturer specifications reveal the difficulty in getting good phantoms/standards to perform actual measurements and for benchmarking x-ray digital radiography and computed tomography systems.

References

Logan, C., A. Waters, and H. Martz, (2004) "*Edges for Digital Radiography & NIF HEDP Capsule Phantoms for Computed Tomography*", Lawrence Livermore National Laboratory, Livermore CA UCRL-ABS-207064.

Appendix

Wall Thickness calculations

Wall thicknesses were calculated using the dimensional measurement tools in the internally developed 'imgrec' code. Two particular tools are important, the line tool, and the automated thickness tool for circular objects. The line tool works in two ways, the user draws a line spanning the feature and the code reports the number of pixels, and the physical distance (pixel distance * physical pixel size). Second, the user draws a line with space on both sides of the wall, and a wall thickness is calculated [Bossi, et al. 2002]. In the more automated tool a series of lines are drawn using the outer surface of the circular object and the center for the equations of the lines, and the wall thickness calculation is performed for each of these lines. The user provides a threshold and a width for bounding the size of the lines. The sequence of calculated thicknesses are generated as a vector (the results are plotted Figures 3-5). If noise becomes a concern, a segmentation routine is used to pre-process the CT reconstructed image before automated wall-thicknesses are calculated. In the case of the LDPE and the copper tubes the wall thicknesses were calculated with the un-segmented data. For the gold tube segmentation pre-processing was used to eliminate a few bad points in the image. However, the calculated thicknesses were compared with the un-segmented data in regions where the signal-to-noise was better and there was very little difference.

Reference

Bossi, Richard, Iddings Frank, Wheeler George C, and Patrick Moore, NonDestructive Testing Handbook, 3rd Edition, Volume 4, Radiographic Testing, Chap13, 2002 ASNT.